

DØ TOP QUARK CROSS SECTION FOR THE 1992-1995 TEVATRON RUN

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We present a measurement of the $t\bar{t}$ cross-section in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV using dilepton and single lepton final states. This analysis uses $\sim 100 \text{ pb}^{-1}$ of data collected with the DØ detector at Fermilab during the 1992-1995 run. Analyses in two other final states are also presented.

1 Introduction

The discovery of the top quark was announced at Fermilab by DØ¹ and CDF² more than one year ago. Since the discovery announcement, DØ has increased the accumulated delivered luminosity by a factor of more than two, for a total of roughly 100 pb^{-1} . Along with the larger data sample we have made advances in understanding the detector. Applicable to the following analyses are improved particle identification and a re-calibration of jet energy corrections.

The analyses presented here show a change in emphasis from searching for top to a measurement of its properties. The event selection is optimized on Monte Carlo to minimize the fractional error on the cross section and not to maximize significance. Those aspects of the DØ top analyses that have changed or improved since the discovery will be presented here. Details of the full analyses can be found elsewhere.^{1, 3}

We assume for our analyses that the top quark is pair-produced and decays 100% of the time into a W boson and a b quark. The cross section measurement is based on signals of $t\bar{t}$ decay through seven distinct channels. The dilepton channels occur when both W bosons decay leptonically ($e\mu + \text{jets}$, $ee + \text{jets}$, and $\mu\mu + \text{jets}$). The single-lepton channels occur when just one W boson decays leptonically ($e + \text{jets}$ and $\mu + \text{jets}$). The single-lepton channels are subdivided into b -tagged and untagged channels according to whether or not a muon is observed consistent with $b \rightarrow \mu + X$. The muon-tagged channels are denoted $e + \text{jets}/\mu$ and $\mu + \text{jets}/\mu$.

We have extended the search for $t\bar{t}$ decay to more of the available decay modes. Preliminary results are presented in the $e\nu + \text{jets}$ channel, characterized by events with very large \cancel{E}_T , and the

all-jets mode defined by a six jet final state.

2 Particle Detection

Muons are detected and their momentum determined using an iron toroid spectrometer located outside of a uranium-liquid argon calorimeter and a non-magnetic central tracking system inside the calorimeter. A full description of the DØ detector and data collection systems is available elsewhere.⁴ Two distinct types of muons are defined. High- p_T muons, which are predominantly from gauge boson decay, are required to be isolated from jet axes by a distance $\Delta\mathcal{R} > 0.5$ in η - ϕ space ($\eta = \text{pseudorapidity} = \tanh^{-1}(\cos\theta)$; $\theta, \phi = \text{polar, azimuthal angle}$), and to have transverse momentum $p_T > 15 \text{ GeV}/c$. Tag muons, which are primarily from b or c decay, are required to be within a distance $\Delta\mathcal{R} < 0.5$ of any jet axis and to have $p_T > 4 \text{ GeV}/c$.

Electrons are electromagnetic energy clusters characterized by a number of variables that describe shower shape and the associated charged track. We select clusters based on the ratio of the joint likelihood of these variables for electrons and background. Using the joint likelihood rather than selection cuts on the individual variables reduces the multijet background by a factor of 2 for the same acceptance. The efficiency for finding electrons was measured from $Z \rightarrow ee$ data. Electrons are required to have $|\eta| < 2.5$ and transverse energy $E_T > 15 \text{ GeV}$.

Jets are reconstructed using a cone algorithm of radius $\mathcal{R} = 0.5$.

The presence of neutrinos in the final state is inferred from missing transverse energy (\cancel{E}_T). The calorimeter-only \cancel{E}_T ($\cancel{E}_T^{\text{cal}}$) is determined from energy deposition in the calorimeter. Correcting

Table 1: Minimum kinematic requirements for the standard event selection (energy in GeV).

Channel	High- p_T Leptons		Jets		Missing E_T		Topological		
	$E_T(e)$	$p_T(\mu)$	N_{jet}	$E_T(\text{jet})$	$\cancel{E}_T^{\text{cal}}$	\cancel{E}_T	H_T	\mathcal{A}	specific
$e\mu + \text{jets}$	15	15	2	20	20	10	120	-	-
$ee + \text{jets}$	20		2	20	25	-	120	-	$ m_{ee} - m_{Z^0} > 12 \text{ GeV}/c^2$
$\mu\mu + \text{jets}$		15	2	20	-	-	100	-	$\text{Prob}(\chi^2_{Z\text{fit}}) < 1\%$
$e\nu + \text{jets}^*$	20		2	30	50	50	-	-	$m_T(e, \cancel{E}_T) > 115 \text{ GeV}/c^2$
$e + \text{jets}$	20		4	15	25	-	180	0.065	$E_T^W > 60 \text{ GeV}$
$\mu + \text{jets}$		20	4	15	20	20	180	0.065	$E_T^W > 60 \text{ GeV}$
$e + \text{jets}/\mu$	20		3	20	20	-	110	0.04	tag muon
$\mu + \text{jets}/\mu$		20	3	20	20	20	110	0.04	tag muon, $\text{Prob}(\chi^2_{Z\text{fit}}) < 1\%$

* Not yet included in cross section measurement.

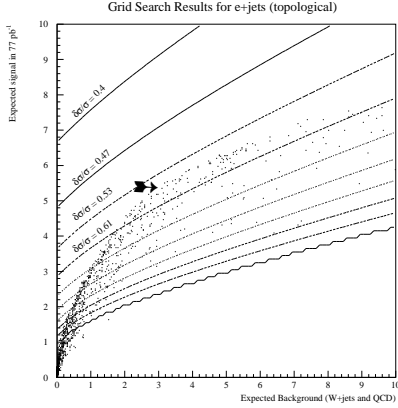


Figure 1: Monte Carlo $e + \text{jets}$ expected signal event yield *vs.* expected background event yield for various values of \mathcal{A} and H_T . Lines are contours of constant relative error on cross section. Arrow denotes point where cuts are chosen, $H_T = 180 \text{ GeV}/c^2$ and $\mathcal{A} = 0.065$.

$\cancel{E}_T^{\text{cal}}$ for the measured p_T of detected muons yields the total \cancel{E}_T .

3 The Counting Experiment

The signature for the dilepton channels is defined as two isolated leptons, two or more jets, and large \cancel{E}_T . The signature for the single-lepton channels is defined as one isolated lepton, large \cancel{E}_T , and three or more jets (with muon tag) or four or more jets (without tag). A summary of the kinematic cuts can be found in Table 1.

Additional special cuts are used in the $ee + \text{jets}$, $\mu\mu + \text{jets}$ and $\mu + \text{jets}/\mu$ channels to remove background from $Z + \text{jets}$. To remove

$Z \rightarrow ee$ background in $ee + \text{jets}$, we require that $|m_{ee} - m_Z| > 12 \text{ GeV}/c^2$, or $\cancel{E}_T^{\text{cal}} > 40 \text{ GeV}$. To remove background from $Z \rightarrow \mu\mu$, the event as a whole is required to be inconsistent with $Z + \text{jets}$ based on a global kinematic fit ($\text{Prob}(\chi^2_{Z\text{fit}})$). H_T is defined as the scalar sum of the jet E_T in the event and is a powerful discriminator between background and top quark production. The definition of H_T for the dilepton channels is slightly modified to include the leading electron E_T .

For the lepton + jets channels we make cuts on aplanarity \mathcal{A} and H_T , and incorporate a new cut on E_T^W defined as the scalar sum of the E_T of the electron (or muon) and \cancel{E}_T . The requirements on H_T and aplanarity were chosen such that the expected fractional error on the cross section measurement is minimized. The cuts were optimized based on studies of Monte Carlo event sets of signal and background using a grid search technique. Figure 1 shows expected signal event yields *vs.* expected background event yields where each point on the plot represents a separate experiment with different choices for cuts on \mathcal{A} and H_T . Overlaid on the same plot are contours of constant fractional error on cross section. Note that the choice for smallest fractional error on the cross section does not correspond to the best possible signal to background ratio.

For the untagged single-lepton channels, the principal backgrounds are from $W + \text{jets}$, $Z + \text{jets}$, and multijet production with a jet misidentified as a lepton. The $W + \text{jets}$ background is estimated using jet-scaling. In this method, we extrapolate the $W + \text{jets}$ cross section from one and two jets to four or more jets assuming an exponential de-

pendence on the number of jets, as predicted by QCD,⁵ and as observed experimentally.

For the tagged single-lepton channels, the observed jet multiplicity spectrum of untagged single lepton background events is convoluted with the measured tagging rate per jet to determine the total background. The tagging rate is observed to be a function of the E_T and η of the jets and is the same within error for both multijet and W +jets events. The background tagging rate averages about 0.4% per jet in the jet E_T range of interest. A systematic error is assigned based on differences in the tagging-rates for dijet, multijet, and gamma+jet data samples.

The acceptance for $t\bar{t}$ events is calculated using the ISAJET event generator⁶ and a detector simulation based on the GEANT program.⁷ Differences in the acceptance found using the HERWIG event generator⁸ are included in the systematic error.

From seven channels, we observe 37 events with an expected background of 13.4 ± 3.0 events (see Table 2). Our measured cross section as a function of the top quark mass hypothesis is shown in Figure 2. Assuming the central DØ top quark mass¹² of $169 \text{ GeV}/c^2$, the production cross section is $5.2 \pm 1.8 \text{ pb}$. The top production cross-section was calculated for the dilepton, tagged, and untagged single-lepton channels independently. All agree well within errors.

4 Two new decay channels

The event topology of the dilepton $e\nu$ + jets mode arises either when one W decays to e, μ , or τ where the corresponding neutrino(s) receives most of the momentum from the W decay or when the neutrinos from both W decays align favorably. Both result in the signature of large \cancel{E}_T . The $e\nu$ channel opens the acceptance to top decays, including contributions from τ 's and regions of phase space from our other dilepton channels where acceptance is low.

The dominant background processes for this channel are $W \rightarrow e\nu$ + jets and QCD production of three jet events where one jet is misidentified as an electron along with a coincident fluctuation in \cancel{E}_T measurement. The most effective reduction of the $W \rightarrow e\nu$ + jets background comes from placing a cut on the transverse mass of the W at 115 GeV . The QCD production of three jet

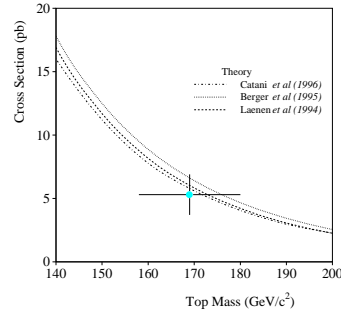


Figure 2: DØ preliminary measured $t\bar{t}$ production cross section (solid line with one standard deviation error band) as a function of assumed top quark mass. Also shown are three theoretical calculations.^{9, 10, 11}

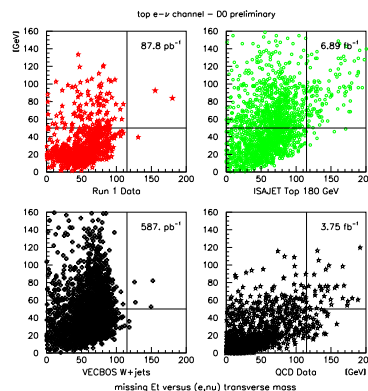


Figure 3: \cancel{E}_T vs. $m_T(e, \cancel{E}_T)$ for data, Monte Carlo signal and $W \rightarrow e\nu$ + jets background, and QCD multijet background. Two data events fall into the signal region.

events is controlled by the cut on the signal's signature of $\cancel{E}_T > 50 \text{ GeV}$. The effectiveness of these cuts (summarized in Table 1) are illustrated in Fig. 3, comparing \cancel{E}_T vs. $m_T(e, \cancel{E}_T)$ for data, Monte Carlo signal and $W \rightarrow e\nu$ + jets background, and QCD multijet background. A preliminary expected event yield of 1.4 ± 0.5 for background and 1.1 ± 0.1 for $m_{top} = 180 \text{ GeV}/c^2$ is calculated for the $e\nu$ + jets mode. Two events are observed passing all cuts.

The signature for the $t\bar{t}$ event in the all-jets channel is six or more high E_T jets with no significant \cancel{E}_T . Although this channel has the largest branching fraction (36/81), a very large background exists from QCD multijet production. For a full description of the all-jets analysis the reader is referred elsewhere.¹³ After applying strict topo-

Table 2: Expected number of top quark events, $\langle N \rangle$, in the seven channels, based on the central theoretical $t\bar{t}$ production cross section of Ref.⁹, for a top mass of 180 GeV/c². Also given are expected background, integrated luminosity, and the number of observed events in each channel.

channel	$e\mu + \text{jets}$	$ee + \text{jets}$	$\mu\mu + \text{jets}$	$e + \text{jets}$	$\mu + \text{jets}$	$e + \text{jets}/\mu$	$\mu + \text{jets}/\mu$	ALL
$\langle N \rangle$	1.7 ± 0.3	0.9 ± 0.1	0.5 ± 0.1	6.5 ± 1.4	6.4 ± 1.5	2.4 ± 0.4	2.8 ± 0.9	21.2 ± 3.8
Background	0.4 ± 0.4	0.7 ± 0.2	0.5 ± 0.3	3.8 ± 1.4	5.4 ± 2.0	1.4 ± 0.4	1.1 ± 0.2	13.4 ± 3.0
$\int \mathcal{L} dt \text{ (pb}^{-1}\text{)}$	90 ± 5	106 ± 6	87 ± 5	106 ± 6	96 ± 5	91 ± 5	96 ± 5	
Data	3	1	1	10	11	5	6	37

logical cuts and requiring a single (double) $b \rightarrow \mu$ tag, 15 (2) events survive in the data with an expected background of 11 ± 2.3 (1.4 ± 0.4) events and a preliminary cross section of 4.4 ± 4.9 (3.9 ± 9.8) pb is obtained. This result is statistically limited but in good agreement with our other cross section results and provides confirmation of the expected excess from $t\bar{t}$ production.

5 Conclusions

We have updated our measurement of the top quark cross section in seven channels in a data sample of roughly 100 pb⁻¹ with improved understanding of particle identification, selection cut efficiency, and jet energy scale. Using the acceptance calculated at our central top quark mass of 169 GeV/c², we measure the top quark pair production cross section to be $\sigma_{t\bar{t}} = 5.2 \pm 1.8$ pb. Preliminary results from analysis of two new decay modes, $e\nu + \text{jets}$ and all-jets, confirm the excess from top production expected in these channels.

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References

1. DØ Collaboration, S. Abachi *et al.*, *Phys. Rev. Lett.* **74**, 2632 (1995).
2. CDF Collaboration, F. Abe *et al.*, *Phys. Rev. Lett.* **74**, , (2)626 (1995).
3. DØ Collaboration, S. Abachi *et al.*, *Phys. Rev. Lett.* **72**, 2138 (1994); *Phys. Rev. Lett.* **74**, 2472 (1995); *Phys. Rev. D* **52**, 4877 (1995).
4. DØ Collaboration, S. Abachi *et al.*, *Nucl. Instrum. Methods A* **338**, 185 (1994).
5. F. Berends, H. Kuijf, B. Tausk, and W. Giele, *Nucl. Phys. B* **357**, 32 (1991).
6. F. Paige and S. Protopopescu, *BNL Report no. BNL38034*, 1986 (unpublished), v6.49.
7. F. Carminati *et al.*, *GEANT Users Guide*, CERN Program Library, December 1991 (unpublished).
8. G. Marchesini *et al.*, *Comput. Phys. Commun.* **67**, 465 (1992).
9. E. Laenen, J. Smith, and W. van Neerven, *Phys. Lett. B* **321**, 254 (1994).
10. E. Berger, and H. Contopanagos, *Phys. Lett. B* **361**, 115 (1995); *Phys. Rev. D* **54**, 3085 (1996).
11. S. Catani, M. Mangano, P. Nason, and L. Trentadue, *Phys. Lett. B* **378**, 329 (1996).
12. S. Protopopescu, *Measurement of the Top Quark Mass at DØ*, submitted to proceedings of the *28th International Conference on High Energy Physics*, Warsaw, (1996).
13. C. Cretsinger, *Search for the Top Quark in the All-Jets Channel*, Ph.D. Thesis, (unpublished) University of Rochester, New York (1995); E. Won, *Top Quark Study in All-Jets Channel at DØ*, submitted to proceedings of the *1996 APS Meeting of the Division of Particles and Fields*, Minneapolis, (1996).